SYSTEMS AND METHODS FOR DETERMINING DEFECT CHARACTERISTICS OF A COMPOSITE STRUCTURE

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FIELD

[0002] The present invention relates generally to the fabrication of composite structures with material placement machines, and more particularly (but not exclusively) to systems and methods for determining defect characteristics of a composite structure, such as defect density-per-unit area and/or cumulative defect width-per-unit area.

BACKGROUND

[0003] Composite structures have been known in the art for many years. Although composite structures can be formed in many different manners, one advantageous technique for forming composite structures is a fiber placement or automated collation process. According to conventional automated collation techniques, one or more ribbons of composite material (also known as composite strands or tows) are laid down on a substrate with a material placement machine. The substrate may be a tool or mandrel, but, more conventionally, is formed of one or more underlying layers of composite material that have been previously laid down and compacted.

[0004] Conventional fiber placement processes utilize a heat source to assist in compaction of the plies of composite material at a localized nip point. In particular, the ribbon or tow of composite material and the underlying substrate are heated at the nip point to increase the tack of the resin of the plies while being subjected to compressive forces to ensure adhesion to the substrate. To complete the part, additional strips of composite material can be applied in a

side-by-side manner to form layers and can be subjected to localized heat and pressure during the consolidation process.

[0005] Unfortunately, defects can occur during the placement of the composite strips onto the underlying composite structure. Such defects can include tow gaps, overlaps, dropped tows, puckers (i.e., raised regions in a tow), and twists. In addition, there are foreign objects and debris (FOD), such as resin balls and fuzz balls, that can accumulate on a surface of the composite structure which must be detected, identified and eventually removed from the ply surface.

[0006] Composite structures fabricated by automated material placement methods typically have specific maximum allowable size requirements for each flaw, with these requirements being established by the production program. Production programs also typically set well-defined accept/reject criteria for maximum allowable number of (i.e., density) of defects-per-unit area and maximum allowable cumulative defect width-per-unit area.

[0007] To ensure that the composite laminates fabricated by fiber placement processes satisfy the requirements pertaining to defect size, the structures are typically subjected to a 100% ply-by-ply visual inspection. These inspections are traditionally performed manually during which time the fiber placement machine is stopped and the process of laying materials halted until the inspection and subsequent repairs, if any, are completed. In the meantime, the fabrication process has been disadvantageously slowed by the manual inspection process and machine downtime associated therewith.

[0008] Recently, systems have been developed that are capable of detecting, measuring, and marking individual defects in the composite structure. Exemplary systems and methods capable of accurately and reliably detecting, measuring and/or marking defects in a composite structure are disclosed in U.S. Patent Application No. 09/819,922, filed March 28, 2001, entitled "System and Method for Identifying Defects in a Composite Structure"; U.S. Patent Application No. 10/217,805, filed August 13, 2002, entitled "System for Identifying Defects in a Composite Structure"; and U.S. Patent Application No. 10/628,691, filed July 28, 2003, entitled "Systems and Methods for Identifying Foreign Objects and Debris (FOD) and Defects During Fabrication of a Composite Structure." The

entire disclosures of U.S. Patent Application Nos. 09/819,922, 10/217,805, and 10/628,691 are each incorporated herein by reference as if fully set forth herein.

[0009] Although these inspection systems have worked well for their intended purposes, the inventors hereof have recognized that it would be even more beneficial to provide systems and methods that are capable of determining a defect characteristic of a composite structure, such as the composite structure's defect density-per-unit area and/or cumulative defect width-per-unit area.

SUMMARY

[0010] Systems and methods for determining a defect characteristic of a composite structure, such as defect density-per-unit area and/or cumulative defect width-per-unit area. In one preferred embodiment, a method for determining a defect characteristic of a composite structure generally includes: determining a first distance from a first reference point of the composite structure to a defect; determining a second distance from a second reference point of the composite structure to the defect; using the first and second distances to establish a reference area of the composite structure; and considering each defect detected within the reference area and producing therefrom a defect characteristic representative of the composite structure.

[0011] The features, functions, and advantages can be achieved independently in various embodiments of the present inventions or may be combined in yet other embodiments.

BRIEF DESCRIPTION OF THE DRAWINGS

[0012] The present invention will become more fully understood from the detailed description and the accompanying drawings, wherein:

[0013] FIG. 1 is a schematic view of an exemplary composite structure illustrating linear and lateral distances to a defect in the composite structure according to one embodiment of the invention;

[0014] FIG. 2 is a perspective view of a compaction roller having a code ring coupled thereto for common rotation therewith and a photo sensor positioned to monitor the code ring according to one embodiment of the invention;

[0015] FIG. 3 is a schematic view of the code ring shown in FIG. 2;

[0016] FIG. 4 is a schematic view of a system according to one embodiment of the present invention;

[0017] FIG. 5 is a perspective view of a system according to another embodiment of the present invention;

[0018] FIG. 6 is a perspective view of a light source according to the system embodiment shown in FIG. 5;

[0019] FIG. 7 is a perspective view of a system according to another embodiment of the present invention;

[0020] FIG. 8 is a perspective view of a light source according to the system embodiment shown in FIG. 7;

[0021] FIG. 9 is an video frame capturing a pucker and a twist in a composite structure;

[0022] FIG. 10 is a view of a computer display and user controls according to one embodiment of the present invention;

[0023] FIG. 11 is a view of an exemplary part model which may be imported from external or third party software according to one embodiment of the present invention;

[0024] FIG. 12 is a view of the part model shown in FIG. 11 with a course grid overlay according to one embodiment of the invention;

[0025] FIG. 13 is a view of the part model shown in FIG. 12 but with the course grid overlay repositioned to represent a change in orientation for the new ply according to one embodiment of the invention;

[0026] FIG. 14 is a view of two computer displays simultaneously displaying the computer display shown in FIG. 10 and the part model and course grid overlay shown in FIG. 13 according to one embodiment of the present invention;

[0027] FIG. 15 is a view of a computer display according to one embodiment of the present invention; and

[0028] FIG. 16 is a view of a computer display according to one embodiment of the invention.

[0029] Corresponding reference characters indicate corresponding features throughout the several views of the drawings.

DETAILED DESCRIPTION OF THE EXEMPLARY EMBODIMENTS

[0030] According to one aspect, the invention provides a method for determining a defect characteristic of a composite structure, such as defect density-per-unit area and/or cumulative defect width-per-unit area. In one embodiment, the method generally includes: determining a first distance from a first reference point of the composite structure to a defect; determining a second distance from a second reference point of the composite structure to the defect; using the first and second distances to establish a reference area of the composite structure; and considering each defect detected within the reference area and producing therefrom a defect characteristic representative of the composite structure.

[0031] Preferred embodiments of the invention provide methods for determining for a reference area or region of a composite structure one or more of the following defect characteristics: a total defect count, total defect width, defect density-per-unit area (i.e., number of defects-per-unit area), cumulative defect width-per-unit area and/or defect location. Various embodiments allow these defect characteristics to be determined as the composite structure is being fabricated, thereby eliminating the need for manual inspection processes and the machine downtime associated therewith.

[0032] In one embodiment, the method generally includes determining a linear distance to a defect along a course being laid by a material placement machine; determining a lateral distance to the defect from a first end of the composite structure; using the linear and lateral distances to establish a reference area; totaling defects within the reference area; dividing the defect total by the reference area to determine a defect density-per-unit area; determining a width for each defect within the reference area; totaling the widths of the defects within the reference area; and dividing the width total by the reference area to determine a cumulative defect width-per-unit area.

[0033] In the exemplary embodiment, the method includes determining both defect density-per-unit area and cumulative defect width-per-unit area. Alternatively, other embodiments can include determining any one or combination of total defect count, total defect width, defect density-per-unit area,

cumulative defect width-per-unit area and/or defect locations. Further embodiments can include determining any one or combination of total defect count, total defect width, defect density, cumulative defect width and/or defect locations for the entire composite structure in which case a reference area need not necessarily be established.

[0034] FIG. 1 illustrates an exemplary composite structure 22, which is generally comprised of a plurality of adjacent tows or strips of composite tape 24. The strips 24 typically include a plurality of fibers embedded in a resin or other material that becomes tacky or flowable upon the application of heat. The strips 24 are arranged on a work surface, such as a table, mandrel, or other tool 26 (FIG. 4), and compacted with a compaction roller 20 (FIGS. 2 and 5) to form the composite structure 22 according to an automated collation technique, such as that described in U.S. Patent Application No. 10/068,735, filed on February 6, 2002, entitled “Composite Material Collation Machine and Associated Method for High Rate Collation of Composite Materials”. The contents of U.S. Patent Application No. 10/068,735 is incorporated herein by reference in its entirety as if fully set forth herein.

[0035] As shown in FIG. 1, eighteen courses or strips 24 have been completed by the material placement machine. That is, the material placement machine has made eighteen passes across a substrate. During each of the passes, the material placement machine has laid down a strip 24 on the substrate.

[0036] With further reference to FIG. 1, the sixth course 23 of the composite structure 22 includes a defect 36 in the form of a tow gap. Additionally, or alternatively, the composite structure 22 can also include other types of defects such as overlaps, dropped tows, puckers, twists, and foreign objects and debris (FOD) with such defects being counted and measured by embodiments of the invention.

[0037] The dashed line 19 represents the linear distance along the sixth course 23 to the defect 36. The dashed line 21 represents the lateral distance to the defect 36 from a first end 11 of the composite structure 22.

[0038] Various methods may be used to determine linear distances along a course to a defect detected in that course. In an exemplary embodiment,

linear distance to a defect along a course can be determined by multiplying the linear velocity of the material placement head unit along the course with the amount of time that has lapsed between when the course began and when the defect is detected.

[0039] When a defect is detected, a signal can be produced that not only indicates defect detection but may also trigger measurement and marking of the defect. Exemplary systems and methods capable of detecting defects in a composite structure are described generally below and in more detail in U.S. Patent Application No. 09/819,922, filed March 28, 2001, entitled "System and Method for Identifying Defects in a Composite Structure"; U.S. Patent Application No. 10/217,805, filed August 13, 2002, entitled "System for Identifying Defects in a Composite Structure"; and U.S. Patent Application No. 10/628,691, filed July 28, 2003, entitled "Systems and Methods for Identifying Foreign Objects and Debris (FOD) and Defects During Fabrication of a Composite Structure." The entire disclosures of U.S. Patent Application Nos. 09/819,922, 10/217,805, and 10/628,691 are each incorporated herein by reference as if fully set forth herein.

[0040] The start and stop of a course can be determined using signals from the machine load cell which indicate whether or not pressure is being applied to the compaction roller 20 (FIGS. 2 and 5). Receipt of a "pressure on" signal from the machine load cell indicates that the compaction roller 20 is in contact with the composite structure 22 and therefore, that a course has been started. Receipt of a "pressure off" signal indicates that the compaction roller 20 is no longer in contact with the composite structure 22, and therefore that a course has been completed. Accordingly, the time between course start and defect detection can be determined by tracking the amount of time elapsing between receipt of the "pressure on" signal from the machine load cell and the receipt of the signal indicating detection of a defect.

[0041] Alternatively, course start and stop can be determined by receipt of a signal from a device employing proximity sensors, lasers, or sound detectors positioned for determining whether or not the compaction roller 20 is in contact with the composite structure 22.

[0042] In one embodiment, the linear velocity of the head unit is determined by determining the angular velocity of the compaction roller 20 and

multiplying the angular velocity by a circumference of the compaction roller 20. Alternatively, other methods can also be used to determine the linear velocity of the head unit, such as by using a radar gun commonly used for law enforcement purposes in monitoring vehicular speeds along roadways.

[0043] Referring to FIGS. 2, 3 and 5, the angular velocity of the compaction roller 20 can be determined by a code ring 1 coupled for common rotation with the compaction roller 20. As shown, the code ring 1 includes alternating contrasting portions 2 and 3, such as alternating black and white segments. In FIG. 3, the code ring 1 includes an outer diameter 4 of about 1.010 inches and an inner diameter 5 of about .844 inches, although other ring sizes can also be employed. In other embodiments, the contrasting portions can be provided directly on the compaction roller 20 (e.g., marked on, painted on, etc.), thereby eliminating the need for the separate code ring 1.

[0044] With further reference to FIGS. 2 and 5, a photo sensor 7 (e.g., an off-the-shelf photo diode, etc.) is positioned to monitor and capture real-time images of the light-to-dark transitions of the code ring 1 as the code ring 1 rotates along with the compaction roller 20. By detecting and counting the light-to-dark transitions of the ring 1, the compaction roller revolutions can be counted and monitored. The frequency at which the light-to-dark transitions occur can be used to establish the angular velocity of the compaction roller 20. Preferably, axial motion in the compaction roller 20 is minimized in order to maintain the distance from the photo sensor 7 to the code ring 1 constant, which, in turn, allows for more accurate determination of the machine head unit's linear velocity.

[0045] In another exemplary embodiment, the linear distance to a defect along a course can be determined by counting the number (whole and fractional) of revolutions the compaction roller 20 makes from the start of the course to the defect and multiplying that number of revolutions by the circumference of the compaction roller 20. By way of example, the photo sensor 7 and code ring 1 can be used to count the number of revolutions of the compaction roller 20 between receipt of the "pressure on" signal from the machine load cell and receipt of the signal indicating that a defect has been detected.

[0046] Various methods can also be employed to determine the lateral distances to defects from the first end 11 of the composite structure 22. See FIG. 1. In one exemplary embodiment, lateral distance to a defect can be calculated by counting the total number of completed courses, not including the course in which the defect resides, and then multiplying the average width of a course by the number of completed courses. This method is particularly effective for tape placement in which each course is the same width, i.e., the width of the tape.

[0047] The total number of completed courses can be determined by tracking or counting receipt of the pressure on/off signals from the machine load cell. Receipt of a "pressure on" signal from the machine load cell indicates that the compaction roller 20 is in contact with the composite structure 22 and has thus started a course. Receipt of a "pressure off" signal indicates that the compaction roller 20 is no longer in contact with the composite structure 22 and has thus completed the course.

[0048] For fiber placement courses in which the width of each course may not be equal, the lateral distances to defects can be accurately determined by employing a "software ruler." More specifically, the lateral distance can be determined by acquiring a digital image of at least the portion of the composite structure including the lateral distance; selecting a pixel set from the digital image that represents the lateral distance; counting the number of pixels comprising the pixel set; and correlating the pixel count with correlation data (e.g., a predetermined relationship between pixel count and distance) to compute an indirect quantitative measurement for the lateral distance.

[0049] The width of a defect can be determined in a similar manner. After a digital image of the defect has been acquired, a pixel set is selected from the digital image that represents the width of the defect. The pixels comprising the pixel set are counted, and the pixel count is then correlated with correlation data (e.g., a predetermined relationship between pixel count and distance) to compute an indirect quantitative measurement for the defect width.

[0050] Alternatively, defect width may be determined by multiplying the linear velocity of the head unit (as determined in a manner described above)

by the amount of time required for the head unit to traverse the distance separating the opposed sides of the defect.

[0051] The reference area can be defined as any region of the composite structure which is currently under inspection for defects and which has a surface area about equal to the surface area of the reference area. Further, the reference area can be sized to include any suitable surface area, such as five square inches, one square foot, etc. In addition, the reference area can be sized in accordance with production requirements to include only a portion of the composite structure. Alternatively, other embodiments can utilize a reference area corresponding in size to the entire composite structure.

[0052] The reference area can be established in various ways. In one exemplary embodiment, the reference area comprises any region of the composite structure that is bounded by the linear and lateral distances to the presently detected defect. For example, and referring to FIG. 1, a reference area can be established for the defect 36 as the rectangular portion of the composite structure 22 defined by the dashed lines 19 and 21 and the composite structure's first end 11 and lower side edge.

[0053] In another embodiment, the reference area comprises any region of the composite structure which is bounded by a predetermined linear distance and a predetermined lateral distance.

[0054] In either of the aforementioned embodiments, the bounded reference areas can be tracked during the inspection, for example, in a lookup table. The lookout table might then be compared to a running tally of defects (e.g., running defect quantity and/or running defect width) during the inspection.

[0055] In yet other embodiments, the reference area is defined as the region of the composite structure which includes the preceding portion of the course in which the presently detected defect resides and all of the completed, preceding courses. For example, and referring to FIG. 1, a reference area can be established for the defect 36 as the first five courses to the left of course 23 and that portion of the sixth course 23 below the defect 36.

[0056] In further embodiments, the reference area is defined as a region of the composite structure which includes the preceding portion of the course in which the presently detected defect resides and a predetermined

number of completed courses immediately preceding the course in which the presently detected defect resides. For example, a reference area can be established for the defect 36 as that portion of the sixth course 23 below the defect 36 and the three courses (i.e., third, fourth and fifth courses) to the immediate left of the sixth course 23 in FIG. 1.

[0057] In certain embodiments, a comparison is made between the cumulative defect width-per-unit area and a maximum allowable cumulative defect width-per-unit area to determine whether a composite structure is acceptable or should be rejected. The maximum allowable cumulative defect width-per-unit area can be set by production requirements. When the cumulative defect width-per-unit area exceeds the maximum allowable cumulative defect width-per-unit area, the manufacturing process can be halted and/or an indicator of unacceptability can be provided, for example, by a user interface 76 (FIG. 4) described below.

[0058] Additionally, or alternatively, certain embodiments include comparing the defect density-per-unit area and a maximum allowable defect density-per-unit area to determine whether a composite structure is acceptable or not. The maximum allowable defect density-per-unit area can be set by the production requirements. When the defect density-per-unit area exceeds the maximum allowable defect density-per-unit area, the manufacturing process may be halted and/or an indicator of unacceptability may be provided, for example, via the user interface 76 (FIG. 4) described below.

[0059] An exemplary system 10 which can be used to detect defects in a composite structure is illustrated in FIG. 4. As shown in FIG. 4, the system 10 includes at least one camera 12 and at least one light source 14. The camera 12 is connected to a processor 66 for interpreting the images the camera 12 captures, or to a storage device 64 for storing the images, or both, as discussed more fully below.

[0060] The light source 14 is positioned to emit light for illuminating the composite structure 22. The illumination is reflected differently by defects in the composite structure than from portions of the composite structure that are defect free. For example, illumination reflecting off non-defective portions of the composite structure 22, and light that fails to reflect off of defects in the

composite structure 22, or vice versa, creates visible images that can be captured by the camera 12. Details regarding systems and methods for identifying defects in a composite structure during fabrication thereof are included in previously referred to U.S. Patent Application Nos. 09/819,922, 10/217,805, and 10/628,691.

[0061] As shown in FIG. 4, the camera 12 is positioned near the composite structure 22 so as to capture images of portion of the composite structure being illuminated, which is typically immediately downstream of the nip point at which a composite tow is joined with the underlying structure. Alternatively, and as shown in FIG. 5, a reflective surface 16 may be positioned near the composite structure (the composite structure is not shown in FIG. 5), and angled such that the reflective surface 16 reflects an image of the illuminated portion of the composite structure. The camera 12 may be positioned to point toward the reflective surface 16 in order to capture close-range images of the illuminated portion of the composite structure from the reflective surface 16. More than one reflective surface 16 may also be utilized in further embodiments of the invention in which the reflective surfaces 16 cooperate in order to direct images of the illuminated portion of the composite structure to the camera 12.

[0062] A wide range of cameras can be used including commercially-available cameras capable of acquiring black and white images. In one embodiment, the camera 12 is a television or other type of video camera having an image sensor (not shown) and a lens 13 through which light passes when the camera 12 is in operation. Other types of cameras or image sensors can also be used, such as an infrared-sensitive camera, a visible light camera with infrared-pass filtration, a fiber optic camera, a coaxial camera, Charge Coupled Device (CCD), or Complementary Metal Oxide Sensor (CMOS). The camera 12 can be positioned proximate the composite structure 22 on a stand (not shown) or mounted to a frame 28 or similar device.

[0063] In those embodiments that do not include a reflective surface 16, the camera 12 may be mounted to the frame 28 by way of a bracket 30 and associated connectors 32, as shown in FIG. 4. The connectors 32 may be rivets, screws or the like that mount the camera 12 to the frame 28 in a stationary position. Alternatively, the connectors 32 may be a hinge-type connector that

permits the camera 12, light source 14, and associated assembly to be rotated away from the composite structure 22. This embodiment is advantageous in situations where other parts of the material placement device, particularly the parts located behind the camera 12 and associated assembly, must be accessed, such as for maintenance, cleaning, or the like.

[0064] FIG. 5 illustrates an alternative embodiment of the hinge-type connector 32 that mounts the camera 12, reflective surface 16, light source 14, and associated assembly (e.g., camera assembly) to the frame 28 by way of a bracket 30. A suitable fastener, such as a thumbscrew or any other fastener that may be removed or loosened with relative ease, can be inserted through hole 34 and then tightened to secure the camera assembly in place for operation. The fastener may be loosened or removed, for example, to rotate the camera assembly away from the compaction roller 20 and other parts of the fiber placement device.

[0065] With further reference to FIG. 4, a filter 15 can be placed on the lens 13 for filtering light in a particular manner. In one embodiment, the filter 15 is designed to filter light such that only the infrared component or a certain infrared wavelength or range of wavelengths of light can pass into the camera 12. In this manner, the filter 15 prevents ambient visible light from entering the camera 12 and altering the appearance of the captured image.

[0066] Other methods of filtering light can also be used to achieve the same, or at least similar, result. For example, the camera may be designed to include a built-in filter of equivalent optical characteristics. In addition, the filter can be located between the camera lens 13 and image sensor. Alternatively, the camera may include an image sensor that is only sensitive in the infrared spectrum (e.g., an infrared-sensitive camera), thus eliminating the need for the filter.

[0067] The light source 14 of the system 10 will now be described in more detail. The light source 14 is positioned to emit light for illuminating at least a portion of the composite structure 22.

[0068] In FIG. 4, the light source 14 is shown positioned at an oblique angle 37 relative to the composite structure 22. The oblique angle 37 may be about forty-five degrees, although other angles are possible depending on the

application. In addition, the light source 14 is also shown positioned to emit light in a direction substantially perpendicular to the direction of placement of the strips 24 in order to highlight the defects 36, as described below.

[0069] Further, the system 10 may include more than one light source. For example, the embodiment of FIG. 5 includes two light sources 14 positioned relative to the composite structure and compaction roller 20 on either side of the reflective surface 16 and camera 12. Another exemplary embodiment that includes two light sources 14 is shown in FIG. 7 in which two linear optical fiber arrays are positioned on opposed sides of the camera 12.

[0070] In FIG. 4, the light source 14 is adjustably positioned relative to the composite structure 22 by mounting or attaching the light source 14 to a mounting apparatus 27. The mounting apparatus 27 can include a main shaft 29, a secondary shaft 31, and a locking clamp 33 for quickly and accurately adjusting the position of the light source 14. The mounting apparatus 27, in turn, can be attached to the frame 28, to the camera 12, to the bracket 30, or to some other object that defines a common position for both the light source 14 and the camera 12 such that the light source 14 and camera 12 maintain a constant spatial relationship relative to one another.

[0071] The quality and magnitude of the surface illumination of the composite structure is greatly affected by ambient lighting and by the reflectivity of the material. Accordingly, embodiments of the invention advantageously employ an infrared light source to more effectively illuminate dark flaws on a dark background. In this regard, the light source 14 can be selected from an infrared light or another type of light having an infrared component, such as a halogen light source (FIG. 6) or other incandescent light sources (not shown). In other embodiments, the light source 14 can also include a fluorescent light source (e.g., white light LEDs, low pressure/mercury filled phosphor glass tube, etc.), a strobe or stroboscopic light source, a noble gas arc lamp (e.g., xenon arc, etc.), metal arc lamp (e.g., metal halide, etc.) and a lasers (e.g., pulsed lasers, solid state laser diode arrays, infrared diode laser arrays, etc.). The light from the light source 14 may also be pumped from through optical fibers to the point of delivery, such as is shown in FIG. 7.

[0072] In some embodiments, the light source 14 is operated at a power level that maximizes, or at least significantly increases, the infrared (IR) component of the light which works well for inspecting dark tow material, such as carbon. In this regard, exemplary power levels in the range of up to about one hundred fifty watts (150W) in the wavelength range of about seven hundred nanometers to one thousand nanometers (700nm-1000nm) have been sufficient. However, the particular power levels and wavelengths for the light source will likely depend at least in part on the camera's speed and sensitivity, speed at which the material is being laid, delivery losses, and reflectivity of the material being inspected, among other factors. For example, in other embodiments, wavelengths and power levels suitable for inspecting highly reflective materials can be employed.

[0073] In the embodiment shown in FIG. 4, the light source 14 may comprise a plurality of LEDs arranged in an array or cluster formation. In one specific embodiment, the light source 14 includes 24 LEDs mounted in an array upon a three-inch square printed circuit board.

[0074] In another embodiment shown in FIGS. 5 and 6, the light source 14 includes four halogen light bulbs 38, although other quantities can also be used.

[0075] In the embodiment shown in FIG. 7, the light source 14 includes two linear optical fiber arrays positioned on opposite sides of the camera 12. The arrays emit light supplied from a remote source (not shown) through an optical fiber bundle 25. An illuminated linear array 14 is shown in FIG. 8.

[0076] Referring back to FIG. 5, the system 10 may further include a light reflection element 18 located near the light source 14. The reflection element 18 include a series of light reflecting surfaces 40 (FIG. 6) that redirect the light towards the desired area to be illuminated. This levels the illumination across the surface and eliminates, or at least substantially reduce, areas of intense light (i.e., hotspots) created by the brightest portion of the light source 14. Hotspots are undesirable because hotspots prevent consistent illumination of the composite structure, which may lead to errors during the processing of the images captured by the camera 12.

[0077] The light reflection elements 40 are particularly advantageous for illuminating curved/contoured surfaces of composite structures because the redirection of the light permits a larger portion of the composite structure to be evenly illuminated.

[0078] As shown in FIG. 6, the reflection element 18 is curved around the light source 14, such as in a parabolic shape. On the surface of the reflection element 18 that faces the light source 14, the reflection element 18 includes curved steps 40 substantially parallel to the light source 14. The distance between and curvature of the steps 40 can be chosen to be sufficient to provide even illumination from the sum of the two light sources, one on either side of the region of interest. This enables the reflection element 18 to provide more consistent illumination of the composite structure 22, which prevents, or at least reduces, image processing errors due to inconsistent illumination of the composite structure 22. Alternatively, the shape and/or surface configuration of the reflection element 18 can be modified in other ways that also produce consistent illumination and scattering of the light produced by the light source 14 over the desired portion of the composite structure 22.

[0079] In an exemplary embodiment, the reflection element 18 has an overall parabolic shape with seventeen parabolic curved steps 40 having a range of widths from about 0.125 inches at the outer edge of the reflection element 18 to about 0.250 inches at the center of the reflection element 18. The reflection element 18 also has a uniform step height of about 0.116 inches. In other embodiments, however, the reflection element may be provided with different numbers of steps having different uniform or varying widths and different uniform or varying step heights.

[0080] Furthermore, the reflection element 18 may be adjusted in order to direct the light produced by the light source 14 and scattered by the reflection element 18 toward the desired portion of the composite structure. For example, as shown in FIG. 6, the reflection element 18 is adjustably mounted to the mounting apparatus 27 with fasteners 42. The loosened fasteners 42 can move within slots 44 to correspondingly adjust the angle of the reflection element 18 relative to the composite structure. Once the reflection element 18 is positioned appropriately, the fasteners 42 are tightened to secure the reflection

element 18 in the desired position. Adjustments of the reflection element 18 can also be enabled by other methods, such as by electronic means that permit remote adjustment of the reflection element 18.

[0081] It has been observed that the composite structure 22 produces high glare when illuminated across the direction of placement of the strips 24 but produces substantially less glare when illuminated along the direction of placement of the strips 24. The systems and methods of at least some embodiments exploit the high-glare/low-glare phenomenon by casting light across the top layer of the composite strips 24 in a direction substantially perpendicular to the direction of placement of the strips 24. This produces a relatively large amount of glare on the top layer of the composite structure 22. The underlying layers, which produce significantly less glare than the top layer because of their orientation, will show through any gaps or other defects in the top layer and thus be easily located. In addition, twists and other surface defects in the top layer will alter the orientation of the strips in the top layer and thus correspondingly alter, i.e., decrease, the glare of the top layer at the defect location.

[0082] While the high-glare/low-glare phenomenon occurs when illuminated with either visible light or infrared light, the filter 15 used in one embodiment of the system 10 substantially removes the glare caused by ambient light such that only the glare caused by the infrared light source is used to locate the defects. Accordingly, the filter 15 removes the interference of ambient light as the composite structure 22 is being examined for defects.

[0083] In any of the system embodiments described herein, there may be one or more cameras 12 and/or one or more light sources 14 with or without reflection elements 18 (collectively referred to as light sources, hereinafter). In addition, the one or more cameras 12 and/or the one or more light sources 14 may be moveable relative to the composite structure. The multiple cameras 12 and/or multiple light sources 14 and the moveability of the camera(s) 12 and/or the light source(s) provides system 10 flexibility in order to capture the most accurate images of the composite structure. Multiple and/or moveable light source(s) 14 permit consistent and sufficient illumination of the desired portion of the composite structure, regardless of the shape of the composite structure.

Likewise, multiple and/or moveable camera(s) 12 enable capturing an accurate image of any area of the composite structure, regardless of the shape of the composite structure. As such, the multiple and/or moveable light source(s) and/or camera(s) are particularly advantageous when illuminating and capturing images of and curved/contoured portions of composite structures. The multiple and/or moveable light source(s) and/or camera(s) are also advantageous in illuminating and capturing images of composite strips having a width that makes it difficult to illuminate and/or capture images of the entire strip, such that the position of the light source(s) and/or camera(s) may be moved over the entire strip, and/or multiple stationary light source(s) and/or camera(s) may be positioned to cover the entire strip. Systems including moveable cameras and light sources are described in detail in previously referred to U.S. Patent Application No. 10/217,805.

[0084] As shown in FIG. 4, the system 10 can also include a marking device 62 for marking the location of defects on the composite structure 22. The marking device 62 may be attached to the frame 28 and be triggered by a processor 66 or similar device when a defect 36 is detected. The marking device 62 may spray or otherwise deposit an amount of ink, paint or the like onto the composite structure 22 in those areas where defects 36 has been detected. The markings on the composite structure 22 enables the location of the defects to be subsequently readily identified either automatically or manually.

[0085] In the particular illustrated embodiment, the marking device 62 is an inkjet marking system that sprays a small spot of compatible ink of a highly visible color onto the surface of the composite structure 22 at the defect location to permit rapid access for repair and disposition. Alternatively, other marking methods can also be used, such as a pump-fed felt-tip marker, spring-loaded marking pen, audio or visual alerts, and the like.

[0086] The camera 12 and/or the reflective surface 16, which along with the light source 14 and any reflection element 18, can be mounted to the head unit to allow the camera 12 to continuously capture real-time images of the composite structure 22 and the strips 24 as the head unit moves across the composite structure 22 and the composite strips 24 are laid down. If the composite structure 22 is not planar, the inspection point should preferably be as

close to the nip point as possible, as described above. If the composite structure 22 is planar, the inspection point can be located further from the placement head unit. In either case, the images can be stored in a memory device 64 for future analysis and/or processed immediately by the processor 66, as discussed more fully below.

[0087] FIG. 9 shows an exemplary raw or unprocessed camera image 68 illustrating a contrast between potential defects, such as a pucker 75 and a twist 77, and the remaining portions of the composite structure 22 that are defect free. In the illustrated embodiment, the potential defects 75 and 77 are shown as black or gray areas, while the remaining non-defective portions of the composite structure 22 remain substantially white 72. Once the potential defects are located, the defects may be marked with the marker 62 and the linear and lateral distances to the potential defects can be determined in a manner describe above.

[0088] With further reference to FIG. 4, the processor 66 may receive the images 68 from the camera 12 or from the memory device 64 in which the images 68 have been stored. The processor 66 may then process and analyze the images to facilitate the reliable detection of defects. In at least one embodiment, the processor 66 and memory device 64 are components of a conventional computer.

[0089] The system 10 may also include a user interface 76 that is in communication with the processor 66. The user interface can be programmed such that it can run from a wide range of software applications, including but not limited to DOS, Windows 98, Windows/NT, Windows 2000, Windows CE, Linux, Unix, and equivalents.

[0090] As shown in FIG. 10, the user interface 76 includes a display screen 80, such as on a computer monitor, and can also include an input device, such as a keyboard and mouse (not shown), for permitting an operator to move a cursor about the display screen 80 and input various system settings and parameters. The display screen 80 can also be touch-sensitive for permitting the operator to input the desired settings by manually touching regions of the display screen.

[0091] The user interface 76 includes a window 81 in which an image 74 of the composite structure 22 is displayed for viewing by the operator or other user. The window 81 can also include a visual display 69 of defect location by course.

[0092] Although the image 74 can be the unprocessed camera image 68 (FIG. 9), the image 74 shown in FIG. 10 can also be a processed image that has been binarized. During binarization, all shades of gray above a predetermined threshold value can be changed to white, while all gray shades below the threshold are changed to black to heighten the contrast of defects and improve the accuracy of defect detection. In other embodiments, the binarization operation need not be performed but instead the raw image, rates of change of the light levels in the raw image, and/or color changes in the images can be used to identify the defects.

[0093] The user interface 76 also provides user controls 78 for allowing various user inputs to the system. In the particular illustrated embodiment of FIG. 10, the user interface 76 allows adjustment to the binarization threshold. Generally, the setting of the binarization threshold involves a tradeoff between the sensitivity with which defects are detected and the resolution with which the defects are depicted. In one embodiment, the binarization threshold is set to about 128 which corresponds to the mid-point on the 8-bit digitizing range of 0 to 255. However, other binarization threshold values can be employed depending at least in part on the particular application, available lighting, camera settings, among other factors.

[0094] The user controls 78 also allow the user to adjust or shift the viewing area within the window 81. During operation, the window 81 displays real-time moving video images of the illuminated portion of the composite structure 22 as the camera 12 and/or the reflective surface 18 are moved relative to the composite structure 22.

[0095] The interface 76 can also allow the user to input the width of course or tow band 71 and maximum allowable cumulative gap width 73.

[0096] In addition to displaying images of the composite structure 22, the display screen 80 also includes a defect table 82 which lists the

discovered defects and provides information for each defect, such as location, size, and the like.

[0097] The display screen 80 can also provide information (which can be continuously updated) such as the number of defects 50, number of courses completed 52 (which may be determined by counting pressure on/off signals from the machine load cell as described above), cumulative defect width 54, and length of the current defect being measured 56.

[0098] The display screen 80 can further include status indicators 84 that notify the user whether a particular image area is acceptable or not acceptable based on predefined criteria, such as maximum allowable dimensional parameters and tolerances.

[0099] The display screen can also include an indicator 85 that notifies the user when the allowable cumulative defect width limit has been exceeded.

[0100] An exemplary embodiment includes importing a part model from external or third party software (e.g., computer aided drafting (CAD) programs, work station-based programs such as Unigraphics (UG) or CATEA, desktop PC applications such as AutoCAD, etc.)

[0101] FIG. 11 illustrates an example of a complex part model 90 imported from third party software. As show in FIG. 12, a course grid overlay 92 can be constructed for the imported part model 90 using the number of courses and the direction of travel that correspond to ply orientation. The diagrammatic concepts of linear and lateral distances 19 and 21 are illustrated in FIG. 12 to show defect 36 location on a surface more complex than the surface shown in FIG. 1.

[0102] After all courses for a ply have been laid, the course grid overlay 92' is repositioned to represent the change in orientation or direction of travel for the new ply, as shown in Figure 13. The interaction between the external or third party software and the software of the material placement machine can be designed to generate an entire set of grids (one for each ply of the part) in advance. These grids can be stored, with the appropriate grid being accessed, called up and positioned at the start of each ply.

[0103] FIG. 14 illustrates another embodiment in which two computer displays are employed for displaying and tracking the various defect data for the imported model 90. As shown, one monitor displays the computer display 80 (previously described above in reference to FIG. 10) while the other monitor simultaneously displays a computer display 180 of the part model 90 and course grid overlay 92. The computer displays 80 and 180 can be continuously updated to show positioning and locations of defects and flaws as they are detected through the vision system interface, described above.

[0104] FIG. 15 illustrates another embodiment 280 in which the display 180' of the part model 90 and course grid overlay 92 are displayed within the window 81' of computer display 80'.

[0105] FIG. 16 illustrates another embodiment 380 in which the display 80" is superimposed or positioned over a corner of the display 180" including the part model 90 and course grid overlay 92.

[0106] Accordingly, embodiments of the present invention provide in-process vision-based inspection systems and methods capable of accurately and efficiently determining various defect characteristics such as total defect count, total defect width, defect density-per-unit area, cumulative defect width-per-unit area and/or defect locations. Embodiments of the invention allow composite structures to be fabricated more efficiently with fewer interruptions than conventional material placement systems which require manual inspections for and measuring of defects.

[0107] Embodiments of the invention permit rapid detection and measurement of the cumulative defect width-per-unit area, and tracking of the defect density-per-unit area. Because this defect information is relatively immediately available and manual measurement is not necessary, machine down-time can be significantly reduced resulting in reduced manufacturing costs and cycle times.

[0108] In addition, embodiments of the present invention allow for ready identification of those composite structures that exceed maximum allowable tolerances pertaining to density and cumulative width of defects. This allows the fabrication process to be halted when maximum allowable tolerances

are exceeded, thereby saving time and materials which would otherwise be lost during continued fabrication of an unacceptable composite structure.

[0109] Further, when too many composite structures are being rejected, an operator can adjust the machines accordingly such that less material is wasted, less labor is expended, and less machine down time is incurred during the fabrication process. Therefore, a lower cost composite structure can be achieved on average.

[0110] Additionally, embodiments also enable improvements in the overall quality of the parts produced because defect density and cumulative defect width can be determined more uniformly and reliably with the various systems and methods of the invention than with manual inspections.

[0111] While various preferred embodiments have been described, those skilled in the art will recognize modifications or variations which might be made without departing from the inventive concept. The examples illustrate the invention and are not intended to limit it. Therefore, the description and claims should be interpreted liberally with only such limitation as is necessary in view of the pertinent prior art.